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Assessment of dry residual biomass potential for use as alternative energy source in the party of General Pueyrredón, Argentina

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The present article assesses the residual biomass availability and its energy potential in the Party of General Pueyrredón, a region located southeast of the province of Buenos Aires, Argentina. These were considered herbaceous and vegetable residues derived from the agricultural activity developed in the region, and forest residues resulting from the pruning of urban trees and garden maintenance. The estimates were based on statistical information of the 2011–2012 harvest and a series of parameters obtained from an extensive literature review. The calculations resulted in an availability of residual biomass of 204,536 t/year, implying an energy potential of 2605 TJ/year. If this biomass is used to generate electricity, it could supply 76,000 users from Mar del Plata city, the largest consumer center in the region. If the same available biomass is used for heat generation, 25,160 users could be supplied by the available residual biomass. The authors concluded that the residual biomass energy potential is significant in the studied region, but a more detailed study must be conducted to assess the techno-economic feasibility of using the available residual biomass as alternative energy source.

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1. Biomass, world overview

The global energy market depends heavily on fossil fuel energy sources such as coal, oil, and natural gas [1,2]. Since it takes millions of years for these fuels to be formed in the earth, their reserves are considered finite, thereby subjected to depletion as they are consumed. The only natural and renewable resource based on carbon that is vast enough to be used as a substitute for fossil fuels is biomass [3,4]. Unlike fossil fuels, biomass is renewable in the sense that only a short period of time is needed to replace what is used as an energy resource [5,6].

The use of biomass for energy generation has gradually declined throughout the humankind history, due to the massive utilization of fossil fuels. Nevertheless, in the nineteenth century biomass still continued to be the main source of primary energy. Currently, it provides 10% of worldwide primary energy (53.3 EJ), and this proportion has not significantly changed in the last decades, as shown in Fig. 1.

Considering the countries' level of development, it can be observed an uneven use of biomass as a primary energy source. While in developed countries[1] it constitutes the most utilized renewable energy source (corresponding to 5% of the primary energy supply, above hydroelectricity with a 2% of contribution), in developing countries' contribution of biomass in the primary energy supply exceeds 8% (see Fig. 2). This three percentage point difference may seem insignificant, but when disaggregating the non-OECD data, as shown in Fig. 3, it can be observed that in African countries biomass represents the main source of primary energy. Similarly, the contribution of this energy source in Asia is substantial, reaching 14.5%, and in non-OECD countries in the Americas, the percentage is almost 20%. In developing countries biomass is mainly used by the residential sector, which consumes 66% of the supplied primary energy, being the main end use for home heating and cooking [7–9].

In recent years the world energy context has changed considerably. The increasing cost of fossil fuels and the technology advances have empowered the development of biomass-based energy systems that are more efficient, reliable, and environmentally friendly [10]. In this context, the concern of many countries to use this renewable energy source as a total or partial alternative to fossil fuels is increasing [11,12].

It is of common knowledge that the development capacity of the biomass sector is still significant, nevertheless the estimates of which will be the contribution of biomass in the future global energy market vary significantly depending upon the literature consulted. According to the study presented by Berndes et al. [13], the contribution of biomass in the global energy supply in 2050 ranges from 100 EJ/year to over 400 EJ/year. For these authors [13], the reason for such significant divergence in the forecasts relay on the uncertainty over two key factors: the availability of land and the energy crops productivity levels.

A more recent study published by the World Energy Council [14], based on an extensive literature review, shows that the worldwide technically available biomass potential may reach 1500 EJ/year in 2050. However, most predictions that take into account sustainability constraints point out a more conservative potential between 200 and 500 EJ/year (see Fig. 4). As seen in Fig. 4, the projection of the primary energy demand for 2050 ranges between 600 and 1000 EJ/year, expecting a bioenergy demand of 250 EJ/year. According to Gadonneix et al. [14], biomass can sustainably supply between one quarter and one third of the estimated primary energy demand for 2050.

According to Long et al. [15] the discrepancy in the results among different projection models is due to the complexity of the factors that influence the bioenergy potential, which has hindered reaching an understanding about the participation of biomass in the future global energy scenario. Furthermore, these authors [15] identify the most controversial factors in the biomass scenarios assessment: climate exchange, technical and economic development, and land availability.

It is important to consider that biomass use may impact, in a competitive way, on some other uses, as food and fodder. Dodić et al. [16] discussed the policy, market conditions and food security of biomass energy sources for supplying the future needs of Vojvodina, Serbia, concluding, in a general way, that international cooperation, regulations and certification mechanisms must be established regarding the use of land, the mitigation of environmental and social impacts caused by biofuel production. Pedroli et al. [17] expressed their worry about how to reach, in a sustainable way, the renewable energy targets of European Union adequately identifying land resources to be used for biomass production and/or harvesting without causing losses in biodiversity. Vávrová et al. [18] present a model for biomass potential assessment under different scenarios of agricultural land utilization, concluding that current biomass potential can be significantly increased with allocation of energy crops on less fertile land according to food security scenarios.

2. Biomass: general aspects

Biomass comprises all biological material derived from living, or recently living organisms. In the context of biomass for energy this is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material [19–21]. Within this definition, biomass for energy can include a wide range of materials, such as: virgin wood, derived from forestry, arboricultural activities or from wood processing; agricultural residues, from agriculture harvesting or processing; industrial waste and co-products, from manufacturing and industrial processes; food waste, from food and drink manufacture, preparation and processing, and post-consumer waste; domestic and municipal waste; and animal manure. These materials contain chemical energy from the solar radiation energy transformation. This chemical energy can be directly released by combustion, or alternatively converted to other energy sources, according to the end used [22].

The reaction between CO_2 in the air, water, and sunlight via photosynthesis produces the carbohydrates that constitute the building blocks of biomass. This process typically converts about 1% of the available solar energy into chemical energy [5,23]. This energy derived from the sun is stored in the chemical bonds of the

[1] In this work it is consider developed countries those members of the OECD organization.

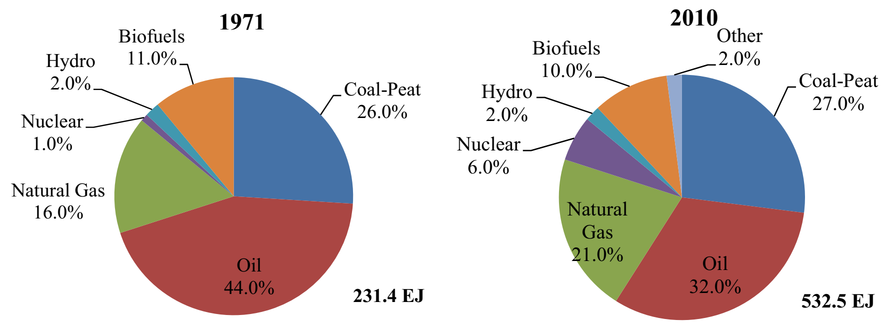

Fig. 1. Worldwide primary energy supply by fuel type, for the years 1971 and 2010 [51].

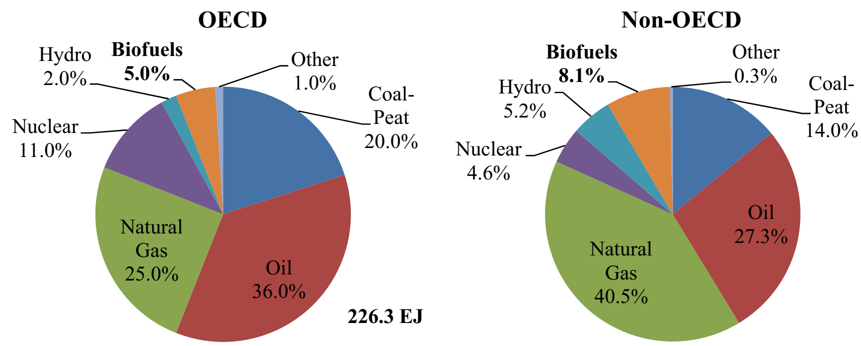

Fig. 2. Total primary energy supply by fuel, for OECD and non-OECD countries, in 2010 [51].

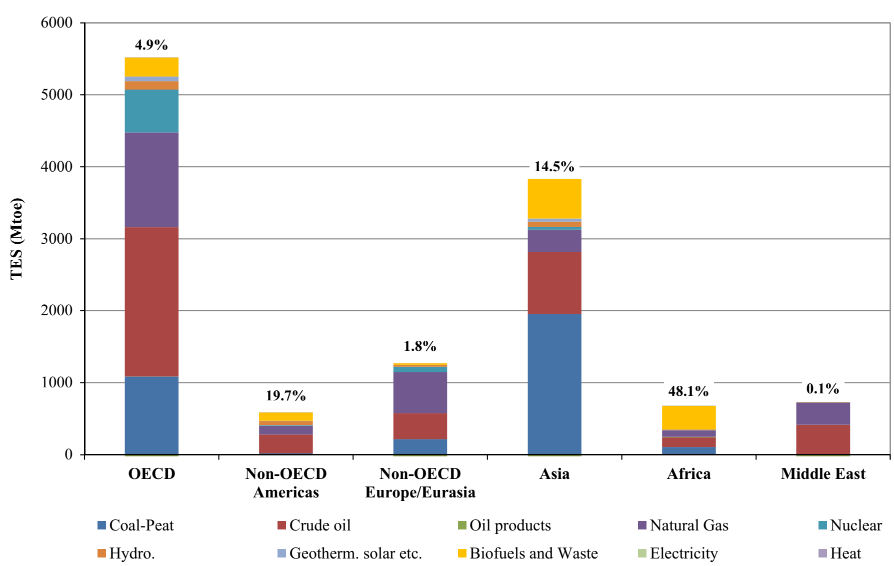

Fig. 3. Disaggregated total primary energy supply by fuel, for OECD countries and non-OECD countries, in 2010 (based on statistics of [51]).

structural components of the biomass. If the biomass is processed to efficiently extract the stored energy in the chemical bonds, and the product is combined with oxygen, the carbon is oxidized to produce CO_2 and water. Thus, the process is cyclical, since the CO_2 is again available to produce new biomass [24].

2.1. Biomass types

There are different types of biomass sources that can be used for energy generation, and therefore many different manners to classify it. One possibility is to classify biomass in accordance with the biological material from which it proceeds, as shown in Fig. 5.

The vegetable biomass residues are organic remainders with the potential for energy generation. They can be spontaneously generated in the nature, or as a result of human activity. In most cases, their final disposal represents a problem to the society [25]. The present work focuses on the study of this type of residues for energy utilization, particularly the ones derived from natural forests and agricultural activities (see gray frames in Fig. 5).

2.2. Biomass energy processes

The conversion of biomass into energy, also referred as bioenergy, embraces a wide range of different types and sources of biomass, conversion technologies, end-use applications, and infrastructure requirements [26]. In each case, the biomass feedstock must be collected, transported, and possibly stored before being

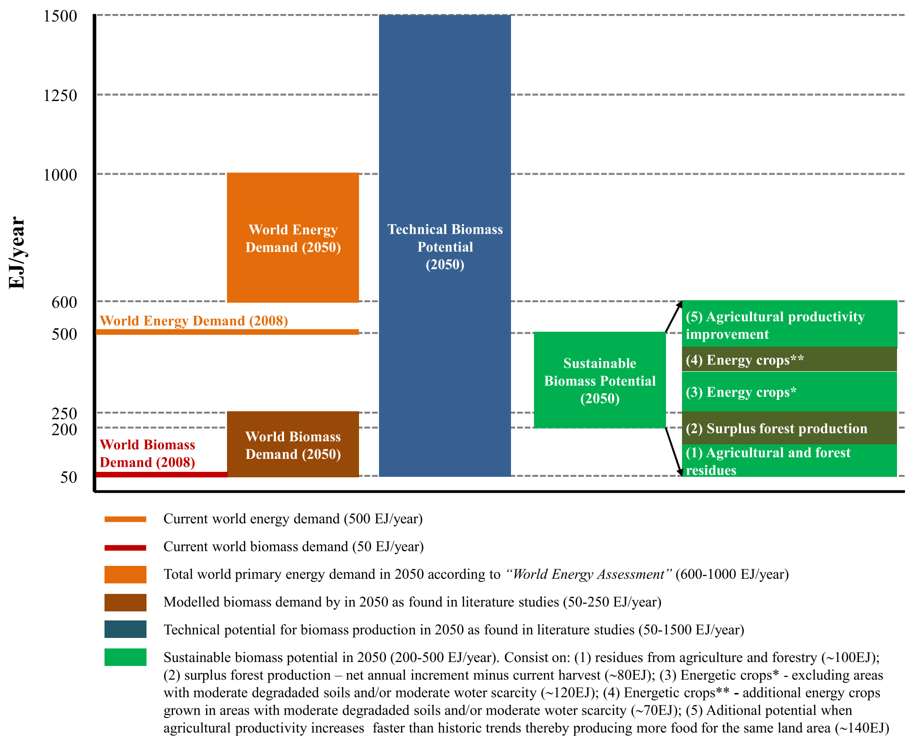

Fig. 4. Technical and sustainable biomass supply potentials and expected demand [14].

processed to make it suitable for the chosen conversion technology.

Biomass can be converted to other usable forms of energy like thermal/electric energy or fuels for the transportation sector, but also, the products of some conversion processes can be used in particular fields, for example as feedstock for synthesis of fine chemicals, adhesives, fertilizers etc. [27]. For the transformation of biomass into energy, two main technological processes are employed: thermochemical processes and biochemical/biological processes. Mechanical extraction (with esterification) is the third technology for the production of energy from biomass [26], though not so widely adopted. In Fig. 6 there are depicted the main conversion routes that are currently used or are under development stage for the production of heat, electricity, and fuels for transportation. Furthermore, in Table 1 it is presented a summary of key features for the different types of biomass conversion technologies with respect to typical range of power, conversion efficiency, and the current state of development of such technologies.

3. Biomass for energy use in Argentina

Argentina's energy mix depends greatly on fossil fuels, which provide 90.6% of the primary energy supply. Natural gas presents the largest share with 51.4% of contribution, followed by oil with 34.9% [28], as depicted in Fig. 7.

Argentina stands out for the production of biodiesel, being among the leading worldwide exporters of this product. In 2012, biodiesel production reached 2455 kt/year [29], representing 8.7% of the world biodiesel production [30]. The country's biodiesel potential is based on the elevated soybean oil capacity production, feedstock used for biodiesel production, positioning Argentina third in the world ranking of soybean production, just behind USA and Brazil.

Bioethanol is largely produced in the North and Northeast regions, where the major sugarcane plantations are situated. Until 2012, the entire bioethanol produced in Argentina (310,000 m^3) came from sugarcane. This production was used for supplying food, beverage, and agricultural chemical industries (37%), and as fuel (63%) blended with gasoline. In 2012, in order to increase the supply for the domestic automotive fuel market, the Argentinian Government approved the production of ethanol from corn and sorghum [31].

The use of biomass for bioethanol and biodiesel production in Argentina is a reality; there are currently large production plants with the appropriate technology and know-how to transform the biomass in large scale. However, the utilization of vegetable biomass, charcoal, agricultural and agro-industrial residues for energy production is not a common practice in the country. These types of biomass feature a great unexploited potential for energy generation (heat and electricity) for supplying the residential, commercial, and industrial sectors. The aforementioned was evidenced by a study conducted by the Argentinian Energy Department and the SAGPyA[2] in partnership with the FOA, in 2009. The research entitled "Analysis of Biomass Energy Balance in Argentina – WISDOM Argentina" aimed quantifying the availability of biomass for energy use in the country. According to the study's results, the available biomass energy potential reaches 1.42 EJ, which represents approximately 40% of the country's primary energy supply, in 2012 (see Fig. 7) [32].

The study conducted by the Argentinian Government has a general character, presenting country level results, which cannot be extrapolated to a smaller scale to assess the availability of biomass in specific areas. For this reason, performing a residual biomass potential assessment in a particular region requires working with official statistical information collected in the local where the study is carried out.

The Argentinian Government has developed various legal instruments for the promotion, incentive, and economical support

[2] SAGPyA – Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food.

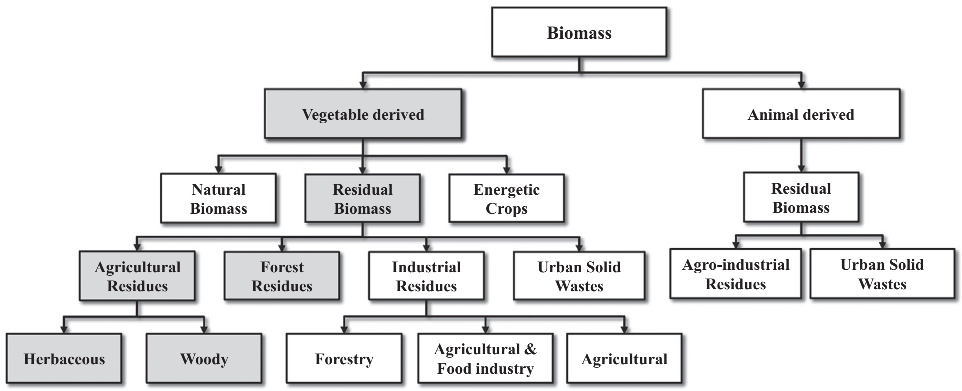

Fig. 5. Classification of biomass according to its origin.

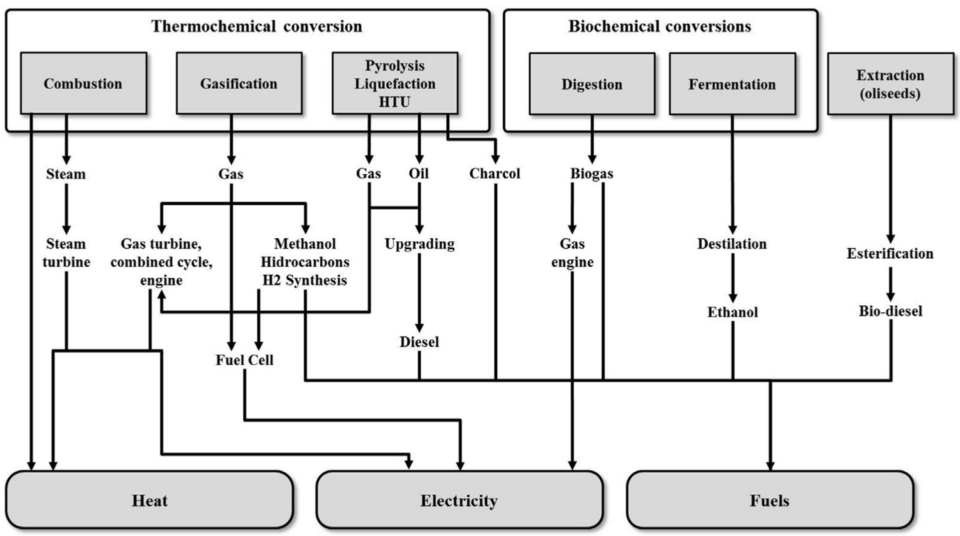

Fig. 6. Main routes for conversion of biomass into energy [9].

of projects based on renewable energy [33]. At a national level, the first legal instrument to incentivize the renewable energy sources was the law 25.019 (*Ley Nacional nro. 25.019 – Régimen Nacional de Energía Eólica y Solar*) for wind and solar energy, which stated wind and solar electricity generation as one of the main national interests. Subsequently, by the end of 2006 it was modified by the law 26.190 (*Ley Nacional nro. 26.190 – Regimen de Fomento Nacional para el uso de fuentes renovables de energía destinada a la producción de energía eléctrica*), establishing a target of 8% of renewable energy participation by 2015 (excluding hydropower) [34]. The promoting instruments are mainly economic; subsides for MWh effectively generated by renewable sources during 15 years, as well as taxes devolution [33].

Currently there are two main programs for the promotion of renewable energies in Argentina: the PERMER (Renewable Energy Project in Rural Markets) program, which started in 1998 with the main objective of providing basic electricity service in a sustainable manner to communities that are still beyond the reach of the grid; and the GENREN (Auction of Electricity Generation from Renewable Sources) program which began in 2009 to contract at least 1GW of renewable energy, to be sold into the grid at fixed rates for 15 years [35]. In the case of biomass, in 2013 PROBIOMASA was created (Project for the Promotion of Energy from Biomass) aiming to boost production, management and sustainable use of biomass for energy purposes. In its initial stage the program targets to generate from biomass a total of 200 electric MW and 200 thermal MW by 2016. This would entail an increase in the share of biomass in the energy mix from current 4.9% to 10% [36].

The Party of General Pueyrredón is an administrative district located in the southeast region of the Buenos Aires Province, Argentina. Hypothetically, this region counts with a good availability of herbaceous biomass-derived residuals, especially from cereals, vegetable biomass residuals derived from the extensive horticultural activity developed in the region, and forest biomass residuals originated in urban tree pruning and garden maintenance. However, there are no works dedicated to estimate the real availability of residual biomass for use as an alternative energy source in this region. Therefore, the present paper has as main objective to assess the actual availability of residual biomass in the Party of General Pueyrredón, and estimate the available energy potential.

In order to accomplish this goal, an extensive literature review was carried out to gather information about the physical properties of the crops found in the region, as well as indices related to the rate of residue generation and its availability for alternative uses.

4. Description of the studied region

The Party of General Pueyrredón is one of the 135 administrative districts of the Buenos Aires Province, located in its southeast region, on the Atlantic coastline (see Fig. 8). The 1492 km^2

Table 1
Overview of key aspects of main technologies used for converting biomass into energy (based on [14,52]).

Conversion option		Typical capacity range	Net efficiency (LHV based)	Status and development			
				R&D	Demonstration	Early Commercial	Commercial
Combustion	Heat	Domestic 5-50kW$_{(thermic)}$ Industrial 1 50MW$_{(thermic)}$	From very low (classic fireplaces) – 10% up to 70-90% for modern furnaces			■	■
	CHP	0.1-1MW$_{(electric)}$ 1-10MW$_{(electric)}$	60-90% (global efficiency) ~ 10% (electric) 80-100% (global efficiency) ~ 15-20% (electric)		■	■	■
	Stand-alone	20-100's MW$_{(electric)}$	20-40% (electric)		■	■	■
	Co-combustion	Typically 5-20MW$_{(electric)}$ for existing coal fired stations, higher for new stations	30-40% (electric)		■	■	■
Gasification	Heat	Typically smaller capacity range around ~100kW$_{(thermic)}$	80-90% (global efficiency)		■	■	■
	CHP (gas engine)	0.1-1MW$_{(electric)}$	15-30%		■	■	
	BIG/CC[3]	30-100MW$_{(electric)}$	40 - 50% (or higher; electric)	■	■		
Pyrolysis	Bio-fuel	Typically smaller capacity range around ~100kW$_{(thermic)}$	60/70% heat content bio-fuel/feedstock	■	■		

[a] Biomass integrated gasification combined cycle.

landscape is mainly flat, with one low altitude mountain range that runs Northwest–Southeast direction known as the Tandilian system (highest point at 1239 m.a.s.l.). Mar del Plata city, head of the party and economic and administrative center of the region, concentrates almost 99% of the 618,989 inhabitants.

The fishing industry, centered in the port of Mar del Plata, is the main economic activity of the region (69% share), followed by agriculture and livestock production (29% share), and mining (2% share) [37]. Within the agricultural sector, the horticultural sector holds the greater economic participation with 66% share, followed by the crop production with 27% of share, and the fruit production with 7%.

The climate is temperate oceanic, with abundant rainfall all year round and moderate temperatures. The annual temperature variation is not high, summers are mild with average temperatures below 22 °C and winters are cold, with temperatures averaging 6 °C.

In this region of Argentina, the original prevailing vegetation types are grassy prairie and grass steppe, which are characterized by the formation of sixty-centimeters to one-meter height clusters, between which grow numerous herbaceous and shrubs species.

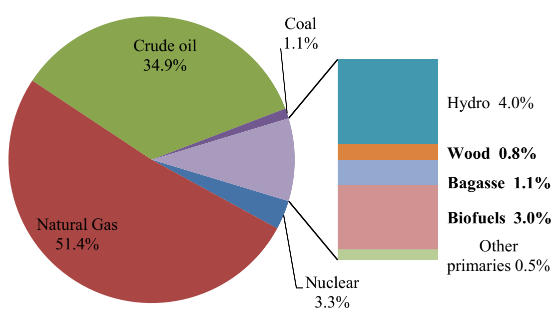

Fig. 7. Argentina's energy matrix. Biomass supplies 4.9% of the primary energy through wood, bagasse, and oil [28].

Traditionally, few trees species grew in this region, but with the advance of civilization and for ornamental and protection purposes, there were introduced some exotic species like eucalyptus, pine, platanus, willows, poplars, oaks, among others. From the time of colonization, the area was mainly utilized for livestock raising. Subsequently, the extensive farming of crop and oilseeds, with annual double crop was introduced. Later on, intensive productive activities, such as horticulture, and the production of fruits and flowers were also adopted [38].

The Buenos Aires Province, where the Party of General Pueyrredón is located, has been identified as a region with significant biomass residues availability that could be potentially used for energy purposes, like electricity and heat generation [32].

5. Materials and methods

5.1. Information sources

The biomass energy potential assessment in the Party of General Pueyrredón was based on statistical information provided by official agencies. The cultivated area and the productivity of various crop species present in the region constitute the base information to begin the analysis.

The study was conducted according to a sectorial approach since there exists differences in the energy use of different types of residues, as well as in other variables, such as the logistics involved for harvesting, handling, storage, heating value, availability of residues etc.

The statistical information used was obtained from the following official agencies:

- National Institute of Agricultural Technology (INTA), Mar del Plata unit, from which statistical information of the 2011–2012 harvest concerning the cultivated area, crop type, and yield of crops, for agricultural herbaceous biomass, cereal crops and horticultural crops was obtained.

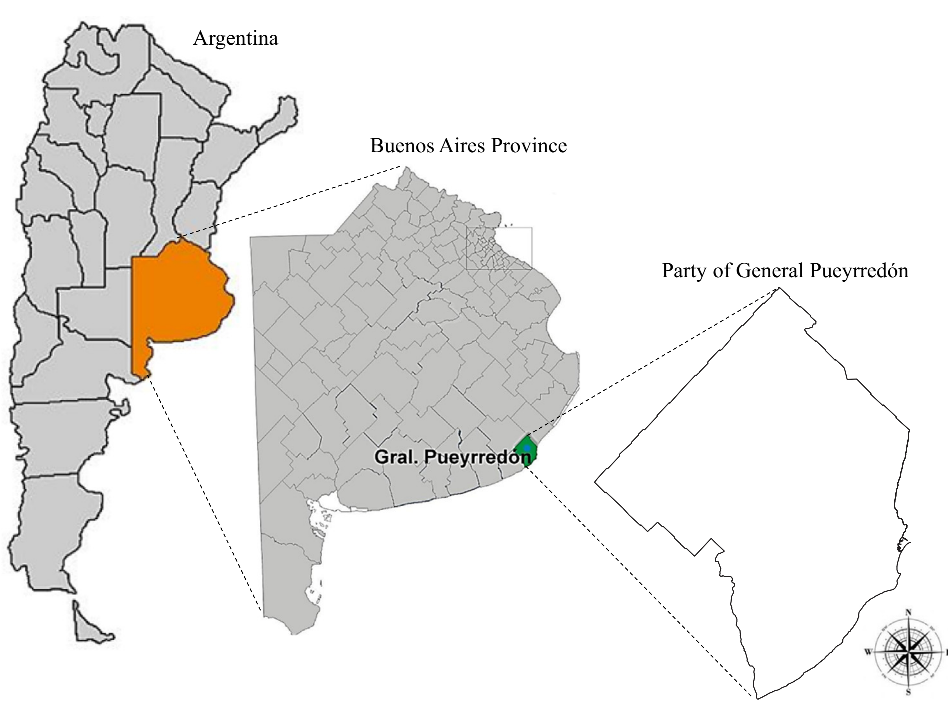

Fig. 8. Location of the Party of General Pueyrredón, Argentina.

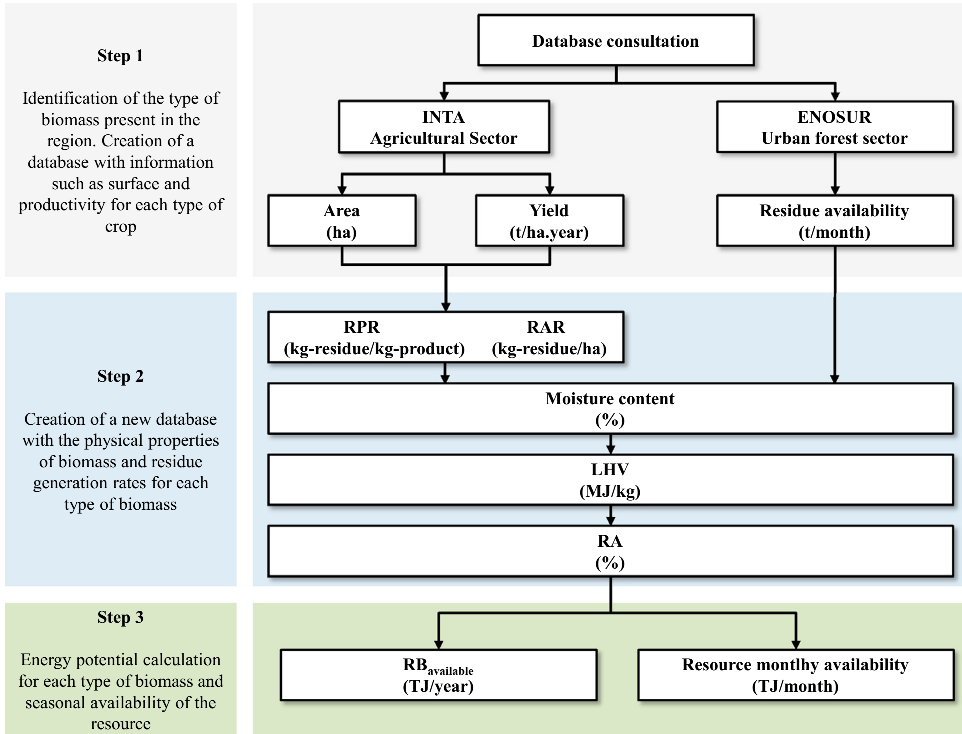

Fig. 9. Methodology used to perform the biomass energy potential assessment. RPR: Residue-to-Product-Rate; RAR: Residue-to-Area-Rate; LHV: Lower Heating Value; RA: Residue Availability; $RB_{available}$: Available Residual Biomass.

Table 2
Types of biomass residues for the energy potential assessment performed in this study.

Biomass types	Subgroup	Species	Type of residue
Agricultural residues	Herbaceous crops	Oat	Straw
		Barley	Straw
		Rapeseed	Straw
		Sunflower	Head, hull
		Corn	Spike, straw
		Soybean	Straw
		Wheat	Straw
	Horticultural crops in open field	Pepper	Biodegradable waste
		Tomato	
		Lettuce	
	horticultural crops in greenhouse	Pepper	
		Tomato	
		Lettuce	
Forest residues	Urban trees	Eucalyptus	Vegetable residues, mainly generated by tree pruning and garden maintenance
		Pine	
		Platanus	
		Other species	

- Division of Urban Forestry, Planning and Services Department (ENOSUR) of the city of Mar del Plata, from which the availability of forest biomass residues derived from the pruning of urban trees in the years 2009 and 2010 was obtained.

Furthermore, additional literature, cited when presenting the corresponding data, was necessary for defining:

- Coefficients to estimate the residual biomass according to crop productivity and cultivated area, for agricultural herbaceous biomass.
- Physical properties of biomass residues; calorific value and moisture content of agricultural herbaceous biomass residues and forest biomass residues.

5.2. Methodology

In order to estimate the available energy potential from residual biomass, the methodology shown in Fig. 9 was developed, which consists of three main steps:

1. Identification and characterization of available biomass in the region of study in terms of types and species of biomass, harvest periods, and geographical location. This step was associated with the creation of a statistical database with the cultivated area and the productivity of all the identified species in the region.
2. Creation of a new database containing the physical properties of biomass and the rate of residue generation for each biomass species.

3. Computation of the energetic potential according to the estimated amount of available biomass residues and its heating value, with characterization of seasonal resource availability.

5.2.1. Identification and characterization of biomass resource

The present study focuses on agricultural herbaceous residual biomass, derived from cereal crops and horticultural crops, as well as on forest residual biomass. The final disposition of this type of residual biomass supposes not only a logistical problem for the community, but also an environmental problem, since the residues of biomass not used for agricultural or livestock purposes are often burned in the open field in an uncontrolled combustion process, thus emitting harmful emissions to the atmosphere. Forest residues are also burned in open dumps, causing similar problems. These facts exalts the necessity of making better use of the biomass residues, for which the generation of energy represents a good alternative [39].

The agricultural crops and forest species assessed in this study are presented in Table 2. In the first and second column of Table 3, the cultivate area (ha) and the crop yield (t/ha) for each species of herbaceous biomass and open field and greenhouse horticultural biomass are indicated. These data were collected in the period 2011–2012, according to the INTA [40].

The total area cultivated with herbaceous biomass corresponds to 34.5% of the total territory of the Party of General Pueyrredón, whereas the horticultural biomass occupies 2.4% of the territory, considering open field and greenhouse plantations. At this point, it is important to state that other species of horticultural crops are grown in the region of study, but these were not included in the calculations due to the lack of information concerning the physical properties of these crops (such as moisture content and LHV), as well as the residue to crop generation rates. According to INTA statistics [40], the total area cultivated with horticultural crops was 6055 ha in 2012, almost twice the area considered in the present work. This fact reveals that the real energy potential of the region may be even greater than the estimations presented in this study.

The highest yield among herbaceous crops corresponds to corn, with more than 6 t per cultivated hectare. With respect to horticultural crops, it is noticed that productivity can be reasonably increased when the same species are grown in greenhouses rather than in the open field, such is the case of tomato and pepper.

5.2.2. Available residual biomass assessment

The energy potential assessment for herbaceous and horticultural biomass was performed from a territorial approach, i.e., taking as base information the surface occupied by each crop. However, for the case of forest biomass, the estimation was founded on information of forest residues availability from the largest urban center in the region, the city of Mar del Plata.

5.2.2.1. Agricultural residual biomass. Once the cultivated area and production yield of each crop were determined, the availability of residual biomass was estimated using the residue production rate for each crop. This coefficient relates the residue production with the crop yield, Residue-to-Product-Rate (*RPR*), or with the cultivated area, Residue-to-Area-Rate (*RAR*).

The first method allows the calculation of the residue production rate in multiple cropping systems, where two or more crops are grown in the same space during a single growing season. However, one drawback of this method is their dependence on the type of species under analysis, and on the weather conditions that may affect the growth process of the plant, therefore varying the *RPR* values in different harvests.

The second method assumes an approximately uniform crop growth within the cultivated area, which is not always true. Also, the agricultural production system adopted may produce different yields for the same field [41]. Therefore, in this study the biomass residue generation is estimated based on the *RPR* since it is considered a more accurate estimator. For some specific types of horticultural biomass, *RAR* was used, due to non availability of *RPR*.

Certain quantity of residual biomass must remain on the field for erosion control, this amount differs by crop type, soil type,

Table 3
Overall results of the residual biomass energy assessment carried out in Party of General Pueyrredón.

Source of residue	*S* (ha)	η (t/ha)	*RPR* (t-residue/ t-product)	*RAR* (t-residue/ha)	*RA* (%)	$RB_{available}$ (t/year)	*w* (%)	*LHV* (GJ/t)	*AE* (TJ/year)	
Herbaceous										
Oat	300.0	2.3	1.3	–	28.0	251.2	15.3	13.7	3.4	
Barley	3897.0	5.2	1.2	–	28.0	6807.4	15.4	13.6	92.3	
Rapeseed	1550.0	2.1	1.6	–	30.0	1564.8	23.8	12.0	18.9	
Sunflower	5120.0	2.1	1.9	–	50.0	10,212.5	22.9	11.5	117.7	
Corn	2410.0	6.3	1.4	–	40.0	8500.8	26.2	11.5	97.9	
Soybean	21,750.0	2.1	2.0	–	56.0	53,655.0	21.6	12.2	656.3	
Wheat	15,350.0	5.4	1.2	–	28.0	27,851.0	15.2	13.8	383.5	
Total herbaceous	**50,377.0**					**108,842.7**			**1370.1**	**52.6%**
Horticultural										
Open field										
Pepper	60.0	13.0	–	21.0	50.0	630.0	12.0	12.0	7.6	
Tomato	250.0	70.0	–	42.0	50.0	5250.0	12.0	13.7	71.8	
Lettuce	2500.0	25.0	1.3	–	50.0	40,625.0	60.0	12.8	521.7	
Greenhouse										
Pepper	50.0	70.0	–	33.0	50.0	825.0	70.0	5.8	4.8	
Tomato	300.0	150.0	–	59.0	50.0	8850.0	70.0	9.0	79.8	
Lettuce	300.0	35.0	1.1	–	50.0	5775.0	70.0	9.0	52.1	
Total hort	**3460.0**					**61,955.0**			**737.8**	**28.1%**
Forest										
Eucalyptus	–	–	–	–	83.0	1686.9	15.1	14.9	25.1	
Pine	–	–	–	–	83.0	1686.9	15.1	15.0	25.4	
Platanus	–	–	–	–	83.0	26,991.2	15.1	14.7	396.9	
Other Species	–	–	–	–	83.0	3373.9	15.1	14.9	50.2	
Total Forest						**33,738.9**			**497.5**	**19.0%**
Total	**53,837.0**					**205,629.9**			**2621.9**	

S cultivated land, η crop yield, *RPR* residue-to-product ratio, *RAR* residue-to-area rate, *AR* availability rate, $RB_{available}$ available residual biomass, *w* moisture content, *LHV* lower heating value, *AE* available energy.

weather conditions and the tillage system used [42]. In the present study it is assumed that the *RPR* and *RAR* coefficients already consider the sustainable amount of biomass that can be collected.

The residual biomass generation was calculated according to Eq. (1), when using the *RPR*, and Eq. (2) when using the *RAR* [43].

$$RB = S\eta\, RPR \tag{1}$$

$$RB = S\, RAR \tag{2}$$

where *RB* represents the annual rate of residual biomass production (t/year), *S* is the cultivated area (ha), and η is the crop yield (t/ha).

This procedure was used to estimate the herbaceous residual biomass and the horticultural residual biomass (open field and greenhouse crops). The different residue production rates found in the literature and the criteria used for selecting the values used in the present work are shown in Tables A.1 and A.2 of Annex A. Only for the tomato and pepper crops, both in open field and greenhouse production, the Residue-to-Area-Rate was utilized. For the rest of the crops, the Residue-to-Product-Rate was used for the calculations.

In addition to the environmental constraints related to the sustainable rate of removed biomass, the availability of crop residues for bioenergy production depends on other competing uses [44]. The main competitive uses of crop residues are fodder for cattle feeding, animal bedding, silage and domestic fuel for heating and cooking purposes [45]. These alternative uses add value to the residue, representing a competition that must be considered when evaluating its possible use for power generation.

In order to consider the aforementioned, we adopt the Residue Availability rate, *RA*(%), which represents the maximum amount of residue that is actually available for energy use (after counting possible competitive uses). The *RA* adopted were taken from the literature. Annex B presents the availability rates referenced in the literature for each type of crop, and the criterion adopted for selecting the values used in this study, which is exhibited in Table B.1. It can be observed that the residue availability rates for most of the cereal crops are low in comparison to horticulture crops and forest species. This is explained by the fact that the residual biomass from cereal crops presents alternative uses already adopted in the production system of the region.

From the rate of residual biomass production and the availability rates, it was possible to calculate the actual amount of available biomass, $RB_{available}$ (t/year), for each type of crop according to the following equation:

$$RB_{available} = RB\, RA \tag{3}$$

5.2.2.2. Forest residual biomass. In the case of forest biomass, information of the residue availability in tons per month provided by the Division of Urban Forestry, Planning and Services Department of the city of Mar del Plata was utilized for the calculations. The total monthly amount of forest residues collected in the community in the period 2009–2010, is shown in Table 4. As observed, the residual biomass availability is quite homogeneous throughout the year.

In order to estimate the amount of residues of each species, the following percentages with respect to the total amount of generated residues were adopted: 5% for eucalyptus, 5% for the pine, 80% for platanus, and 10% for other species [45].

Finally, for calculating the actual available forest biomass, Eq. (3) was utilized along with the residue availability rates corresponding to forest biomass, as shown in Table B.1 of Annex B.

5.2.3. Calculating the energy potential derived from residual biomass

Once the available residual biomass was calculated, the energy potential (TJ/year) can be estimated using the Lower Heating Value (LHV) and the moisture content of each type of biomass. The

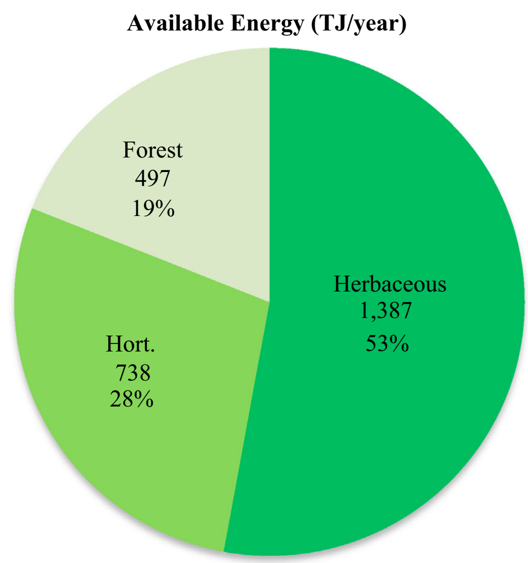

Fig. 10. Energetic contribution of each type of biomass.

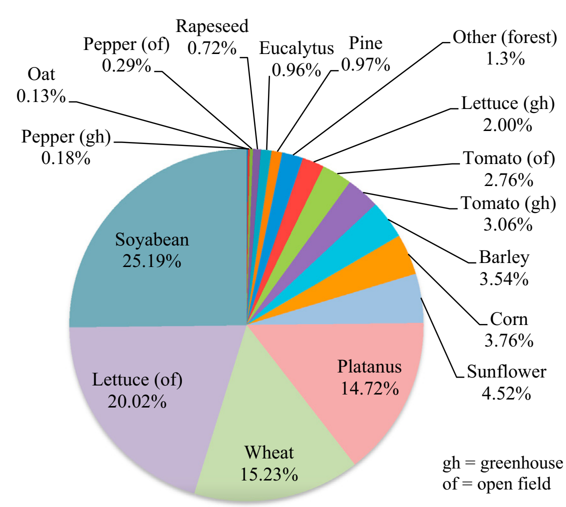

Fig. 11. Energy contribution of each type of crop assessed.

Table 4
Forest residual biomass generated in the city of Mar del Plata, monthly average values corresponding to the period 2009–2010 (t/month).

Species	January	February	March	April	May	June	July	August	September	October	November	December
Eucalyptus (5%)	151.05	165.06	160.43	230.10	195.30	182.55	135.70	131.75	167.34	172.92	167.34	172.92
Pine (5%)	151.05	165.06	160.43	230.10	195.30	182.55	135.70	131.75	167.34	172.92	167.34	172.92
Platanus (80%)	2416.76	2640.96	2566.80	3681.60	3124.80	2920.80	2171.24	2108.00	2677.50	2766.75	2677.50	2766.75
Other Species (10%)	302.10	330.12	320.85	460.20	390.60	365.10	271.41	263.50	334.69	345.84	334.69	345.84
Total	**3020.95**	**3301.20**	**3208.50**	**4602.00**	**3906.00**	**3651.00**	**2714.05**	**2635.00**	**3346.88**	**3458.44**	**3346.88**	**3458.44**

moisture content at which the LHV is expressed corresponds to the amount of moisture of the biomass according to the residue production rate adopted [43].

The LHV was calculated using the Higher Heating Value (HHV) on a dry basis, i.e., 0% moisture content, and the biomass residue moisture content, with the following equation [46]:

$$LHV_w = HHV_0\left(1-\frac{w}{100}\right)-2447\frac{w}{100}-2447\frac{h}{100}901\left(1-\frac{w}{100}\right) \quad (4)$$

where LHV_w is the Lower Heating Value (MJ/kg) at moisture "w"; HHV_0 is the Higher Heating Value (MJ/kg) in dry basis; w is the moisture content on mass fraction; and h is the hydrogen content on mass fraction (adopted as 6%, in dry basis).

Annex C presents the values found in the literature for the HHV_0 (see Tables C.1–C.3) and the moisture content for each type of crop (see Tables C.4–C.6). The values adopted for the present study are described in Table 3.

The available energy derived from the residual biomass (TJ/year) was calculated using the following equation:

$$AE = RB_{available}LHV_w \quad (5)$$

6. Results and discussion

The calculations performed using the information of the Party of General Pueyrredón resulted in an estimated generation of agricultural and forest residual biomass of 204,536 t per year, which implies an energy potential of 2605 TJ/year. The overall results of the analysis are depicted in Table 3.

From the total amount of residues, 53% derive from the agricultural herbaceous crops, followed by the vegetable crops (open field and greenhouse cultivations) with a share of 28%, and finally the forest biomass with 19% (see Fig. 10).

The share of each type of crop is presented in Fig. 11. The soybean presents the highest energy potential among all types of crops evaluated; this is due to the high levels of productivity achieved by this type of crop in the pampa region, and also due to the elevated availability rate of its residues, which do not present meaningful alternative uses. The soybean, the lettuce grown in open field, the wheat, and the platanus provide 75% of the total estimated energy, with 1958 TJ/year.

Within the group of herbaceous crops, wheat and soybean provide 40% of the total calculated energy potential due to the elevated yields presented by these crops in the region of study. If considering solely the herbaceous crops, soybean contributes with 48% of the energy potential.

With respect to the horticultural crops derived from the horticultural activity developed in the region, lettuce is the crop that provides the greatest energy potential (20% of the total). This is due to the vast area cultivated with this crop and its elevated residue availability rate of (nearly 50%). Considering only the horticultural biomass group, the lettuce contributes with 80% of the potential energy. At this point, it is worth mentioning that the crops when grown in greenhouse present a lower energy potential with respect to the ones cultivated in open field. In the first case the energy potential results 55–25% lesser than the latter case. This is due to the great moisture content of the residues derived from greenhouse crops, which do not have the natural drying process after being harvested, as the open field crops residues have.

Within the urban trees species assessed, the platanus presents the highest energy contribution, with 14.72% of the total energy potential, since it is the tree species with highest presence in the urban forest of the city of Mar del Plata. Considering only the residual forest biomass, the contribution of the platanus to the energy potential of this group is 80%.

In an ideal scenario, the biomass resource availability should match the demand side, whether it is used for electricity or heat generation. In order to analyze the resource's seasonality, Fig. 12 shows the residual biomass availability in t/month, calculated from the agricultural crops' harvest calendar (herbaceous and horticultural) and the statistical data of forest residues generation. The monthly distribution presents two peaks of production in the months of March–April–May, and November–December, which corresponds to the harvesting times for the main herbaceous cereal crops in the region. Forest residues provide a homogeneous resource throughout the year, due to the periodic maintenance activity that befalls in the city's trees and gardens.

With respect to the energy demand in the region of study, the period of highest electricity consumption correspond to summer, since from December to February the tourist season occur, along with a large influx of tourists. On the other hand, the highest natural gas consumption for heating purposes takes place during winter months, peaking in June, July, and August.

Considering a scenario where the residual biomass is used for electricity generation and adopting an efficiency of transformation of the resource into electrical power of 40% (excluding the cost of generation) [47], the residual biomass has the potential to provide almost 23% of the electricity consumed in the city of Mar del Plata (291 GWh/year), the largest urban center in the region. This means supplying approximately 180,000 inhabitants.

If, on the other hand, the residual biomass is used for heat generation, and considering in this case a 70% conversion efficiency [48], the resultant energy potential equals to approximately 10% of the natural gas consumption, the main source of residential heating of the city. This means furnishing approximately 25,160 users.

Supply costs are arguably the biggest constraint to widespread use of residual biomass in bioenergy systems. The costs of biomass supply include the fixed and variable costs of biomass extraction and aggregation and the variable costs of transportation to final end-users [49]. In the present study, it was assumed that consumers are located in the same region where the biomass residues are generated and collected, as well as where the heat and electricity are being

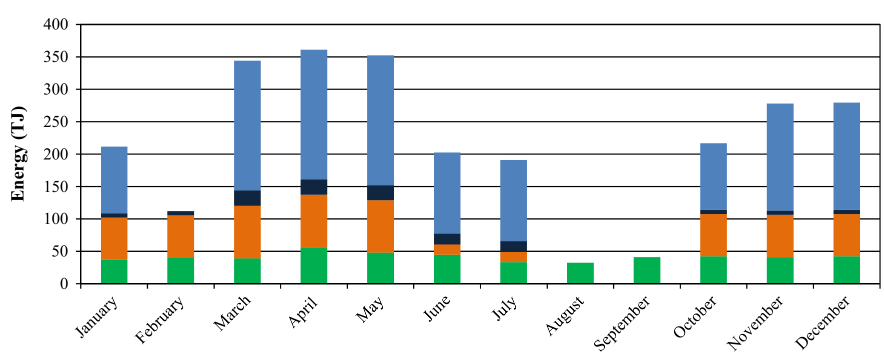

Fig. 12. Seasonal distribution of the residual biomass resource.

produced, as a distributed generation system. Although costs assessment is out of the scope of the present analysis, collection costs must be summed to transportation costs, establishment costs, seed/fertilizer/chemical costs, fuel, labor, repairs and maintenance costs to compose the basis for economic attractiveness of enterprises like this [50].

Considering the results obtained in the present work, it can be said that the residual biomass available in the Party of General Pueyrredón can be used as an alternative energy source for complementing the traditional power generation sources, both for electricity generation and for heating purposes.

However, more detailed studies on the heat/power consumption profile of the community as long as technical and economic surveys on the technological alternatives that could be used for residual biomass transformation into energy must be carried out in the future.

7. Conclusions

In the present work it was assessed that the energy potential of residual biomass derived from herbaceous and horticultural crops, and urban forests in the Party of General Pueyrredón, Argentina. For this, the types of available biomass were identified, and the crop species present in the region were classified. Statistical information concerning the cultivated area and the crop yields were obtained from official agencies. Also, the residue generation rates, as well as the physical properties (LHV and moisture content) of the different biomass species were obtained from an extensive literature review. Finally, the energy potential was calculated based on the above information.

The calculations resulted in an availability of biomass residues of 204,536 t/year, implying an energy potential of 2605 TJ/year. From the total amount of residues, 53% derive from the agricultural herbaceous crops, followed by the open-field and greenhouse horticultural crops with a share of 28%, and finally the forest biomass with 19%.

If this biomass is used to generate electricity, it could supply 23% of the Mar del Plata city's consumption, the largest consumer center in the region. Likewise, if the same available biomass is used for heat generation, it could supply 10% of the total heating needs, reducing the current dependence on natural gas.

The residual biomass could be used as an alternative energy source to the traditional generation sources used in the region (mainly thermal generation), both for electricity and thermal generation, since their seasonal availability coincides with the periods of highest thermal and electrical demand.

Taking into account the aforementioned considerations, it can be concluded that the potential of residual biomass in the Party of General Pueyrredón is relevant and should be included in the municipal and national energy action plans. This is particularly important if we consider that not all the residual biomass available in the region was computed, not all horticultural species present in the region were assessed, and in the case of forest biomass, we used data from only one district's city.

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Annex A

Tables A.1 and A.2.

Table A.1
Residue generation rates for different crops according to literature review (kg-residue/kg-product).

RPR													
Reference	**Herbaceous**							**Horticultural open field**			**Horticultural greenhouse**		
	Oat	**Barley**	**Rapeseed**	**Sunflower**	**Corn**	**Soybean**	**Wheat**	**Pepper**	**Tomato**	**Lettuce**	**Pepper**	**Tomato**	**Lettuce**
[53]	0.86	0.86	–	1.40	–	–	0.86	–	0.03	–	–	–	–
[39]	1.30	1.30	1.70	2.00	1.00	–	1.30	–	–	–	–	–	–
[54]	1.35	1.35	–	–	2.73	–	1.20	–	–	–	–	–	–
[47]	1.30	1.30	–	1.50	–	–	1.20	–	–	–	–	–	–
[47]	1.30	1.30	1.30	1.30	1.30	1.30	1.30	–	0.40	–	–	–	–
[55]	1.30	1.30	–	1.50	2.00	–	1.20	–	–	–	–	–	–
[56]	1.30	1.30	–	1.50	2.00	–	1.20	–	0.10	–	–	–	0.85
[57]	1.40	1.00	–	2.00	1.40	–	1.20	–	–	–	–	–	–
[58]	1.60	1.00	–	1.20	1.40	–	1.30	–	–	–	–	–	–
[59]	0.79	0.81	–	1.41	0.57	–	1.00	–	–	–	–	–	–
[60]	2.44	2.67	–	4.53	3.77	–	1.57	–	–	–	–	–	–
[61]	–	–	–	2.10	1.40	2.10	1.30	–	–	–	–	–	–
[62]	–	–	–	–	1.00	–	–	–	–	–	–	–	–
[63]	1.75	1.75	–	–	0.27	–	1.75	–	–	–	–	–	–
[64]	–	–	–	–	2.00	3.50	1.75	–	–	–	–	–	–
[65]	–	1.00	–	0.88	0.65	–	1.00	–	–	–	–	–	–
[66]	–	–	–	–	–	–	–	–	–	–	–	–	0.85
[67]	1.36	1.06	–	2.06	(Stalk) 1.29	1.70	1.36	–	0.30	–	–	–	–
[67]	–	–	–	–	(Husk) 0.24	–	–	–		–	–	–	–
[68]	0.70	0.80	–	2.00	0.75	1.50	0.70	–	0.30	–	–	–	–
[69]	1.30	1.20	–	2.10	1.00	2.10	1.30	–	–	1.30	–	–	1.30
[44]	1.14	0.93	1.71	2.40	1.00	–	1.34	–	–	–	–	–	–
Adopted	**1.25**	**1.17**	**1.57**	**1.84**	**1.31**	**2.03**	**1.19**	–	–	**1.30**	–	–	**1.10**

Table A.2
Residue generation rates for different crops according to literature review (kg-residue/ha) – humid.

RAR													
Reference	**Herbaceous**							**Horticultural open field**			**Horticultural greenhouse**		
	Oat	**Barley**	**Rapeseed**	**Sunflower**	**Corn**	**Soybean**	**Wheat**	**Pepper**	**Tomato**	**Lettuce**	**Pepper**	**Tomato**	**Lettuce**
[25]	4650	4650	4650	4650	4650	4650	4650	–	–	–	–	–	–
[56]	–	–	–	–	–	–	–	–	–	–	28,500	28,500	28,500
[66]	–	–	–	–	–	–	–	–	–	–	28,000	48,000	28,500
[68]	1400	2700	–	4000	5250	5200	2050	–	–	–	–	–	–
[70]	1260	2120	–		7170		2895	–	–	–	–	–	–
[71]	–	–	–	–	–	–	–	21,000	42,000	–	33,000	59,000	–
Adopted	–	–	–	–	–	–	–	**21,000**	**42,000**	–	**33,000**	**59,000**	–

In the present work the RPR and the RAR coefficients already consider the sustainable amount of biomass that can be collected. The average values adopted for energy potential assessment study are shown in the last row of Tables A.1 and A.2.

Annex B

Table B.1.

Table B.1
Residue availability rates for different crops according to literature review (%).

Reference	**Herbaceous**							**Horticultural**			**Forest**[a]			
	Oat	**Barley**	**Rapeseed**	**Sunflower**	**Corn**	**Soybean**	**Wheat**	**Pepper**	**Tomato**	**Lettuce**	**Eucalyptus**	**Pine**	**Platanus**	**Other species**
[32]	–	–	–	–	–	–	–	–	–	–	83	83	83	83
[65]	15.00	15.00	15.00	35.00	35.00	15.00	15.00	–	–	–	–	–	–	–
[67]	15.00	15.00	–	60.00	37.50	100.00	15.00	95.00	95.00	95.00	–	–	–	–
[68]	50.00	50.00	–	95.00	70.00	100.00	50.00	95.00	95.00	95.00	–	–	–	–
[69]	35.00	35.00	35.00	35.00	35.00	35.00	35.00	–	–	–	–	–	–	–
[70]	15.00	15.00	–	–	30.00	–	15.00	–	–	–	–	–	–	–
[72]	30.00	30.00	30.00	30.00	30.00	30.00	30.00	–	–	–	–	–	–	–
[44][b]	31.50	31.50	39.40	39.40	39.40	–	31.50	–	–	–	–	–	–	–
Adopted	**27.40**	**27.40**	**29.90**	**49.10**	**39.60**	**56.00**	**27.40**	**95.00**	**95.00**	**95.00**	**83**	**83**	**83**	**83**

[a] In the present work the average of the residue availability rates proposed in the literature was adopted. In the case of forest biomass, the residue availability is usually expressed in terms of the "Woodfuel Fraction Factor" which indicates the percentage of biomass over the soil that can be utilized, excluding the leaves and small branches which need to be left in the soil because they are essential to nutrient conservation, this value is 83% for open formations [32].

[b] Ref. [44] that does not take into account the competitive use of residues, thus it is assumed that the percentage of residual biomass that would be available for bioenergy after considering competitive uses (animal fodder, bedding and silage) is 78.7% [73–75].

Annex C

Tables C.1–C.6.

Table C.1
Values of Higher Heating Value (MJ/kg) on a dry basis referenced in the literature, for the different herbaceous crops considered in this study.

Reference	**Oat**	**Barley**	**Rapeseed**	**Sunflower**	**Corn**	**Soybean**	**Wheat**
[39]	17.92	17.92	17.62	10.64	17.78	–	17.92
[41]	–	–	–	–	23.86	–	–
[54]	17.45	17.45	17.45	17.45	17.45	17.45	17.45
[47]	19.64	19.64	19.64	19.64	19.64	19.64	19.64
[55]	18.58	18.57	–	16.98	18.42	–	18.58
[56]	19.42	19.33	–	17.75	18.77	–	19.27
[62]	–	17.43	–	–	8.74	–	18.57
[63]	16.33	16.32	–	–	19.13	16.32	16.96
[65]	–	17.48	–	17.61	17.61		17.48
[67]	17.10	17.10	17.10	17.10	17.10	17.10	17.10
[68]	17.00	17.00		17.00	17.00	17.00	17.00
[44]	17.50	17.50	17.50	17.50	17.50	17.50	17.50
[70]	17.40	17.50	–	–	18.40	–	17.90
[72]	–	17.50	–	–	–	–	17.20
[76]	–	–	–	–	17.57	–	19.08
[77]	18.00	18.00	18.00	18.00	18.00	18.00	18.00
Adopted	**17.85**	**17.77**	**17.88**	**16.97**	**17.80**	**17.57**	**17.98**

Table C.2
Values of Higher Heating Value (MJ/kg) on a dry basis referenced in the literature, for the different horticultural crops considered in this study.

Reference	Horticultural open field			Horticultural greenhouse		
	Pepper	Tomato	Lettuce	Pepper	Tomato	Lettuce
[56]	–	18.48	37.40	37.04	37.04	37.04
[57]	–	18.48	–	–	–	–
[61]	–	16.15	–	–	–	–
[66]	15.26	14.83	–	–	–	–
[67]	–	17.10	–	–	–	–
[68]	–	16.00	–	–	–	–
[77]	18.00	18.00	–	–	–	–
[78]	–	18.17	–	–	–	–
[79]	11.45	–	–	–	–	–
[80]	15.90	–	–	–	–	–
[81]	–	–	–	15.39	–	–
Adopted	**15.30**	**17.15**	**37.04**	**26.21**	**37.04**	**37.04**

Table C.3
Values of Higher Heating Value (MJ/kg) on a dry basis referenced in the literature, for the different forest biomass considered in this study.

Reference	Eucalyptus	Pine	Platanus
[72]	20.48	20.48	20.48
[77]	19.00	19.00	19.00
[79]	18.77	17.78	17.08
[82]	–	–	19.08
[83]	20.00	20.00	20.00
[84]	–	20.48	20.48
Adopted	**19.30**	**19.47**	**19.03**

Table C.4
Values of moisture content (%) referenced in the literature, for the different herbaceous crops considered in this study.

Reference	Oat	Barley	Rapeseed	Sunflower	Corn	Soybean	Wheat
[73]	–	–	–	–	–	15.50	–
[39]	15.00	15.00	40.00	40.00	25.00	–	15.00
[40]	–	–		10.00	–	–	–
[54]	25.00	25.00	25.00	25.00	25.00	25.00	25.00
[47]	15.00	15.00	15.00	15.00	15.00	15.00	15.00
[55]	12.00	12.00	–	12.00	12.00	–	12.00
[56]	12.00	12.00	–	12.00	12.00	–	12.00
[62]	–	17.00	–	–	22.00	–	17.00
[63]	15.00	15.00	–	–	7.53	15.00	18.00
[65]	–	15.00	–	20.00	20.00	–	15.00
[67]	15.00	15.00	–	40.00	52.50	–	15.00
[68]	15.00	15.00	–	40.00	55.00	52.50	15.00
[69]	–	14.50	–	–	–	–	–
[44]	15.00	15.00	40.00	40.00	30.00	–	15.00
[70]	15.00	15.00	–	–	55.00	–	15.00
[71]	–	–	–	–		–	13.50
[76]	–	–	–	–	11.50	–	–
[76]	–	–	–	–	8.60	–	9.20
[77]	15.00	15.00	15.00	15.00	15.00	15.00	15.00
[76]	14.00	–	–	–	–	–	–
[80]	–	–	–	–	–	13.00	–
Adopted	**15.30**	**15.40**	**23.80**	**22.90**	**26.20**	**21.60**	**15.20**

Table C.5
Values of moisture content (%) referenced in the literature, for the different horticultural crops considered in this study.

Reference	Horticultural open field			Horticultural greenhouse		
	Pepper	Tomato	Lettuce	Pepper	Tomato	Lettuce
[56]	12.00	12.00	60.00	70.00	70.00	70.00

Table C.6
Values of moisture content (%) referenced in the literature, for the different forest biomass considered in this study.

Reference	Eucalyptus	Pine	Platanus	Other species
[72,77,79,82–84]	15.10	15.10	15.10	15.10

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